PROCESSING TEST DATA GENERATED BY HIGH SURGE CURRENT TESTS ON A FUSELAGE-LIKE TEST SETUP

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Abstract: In two laboratories, one high voltage and the other one high current, various metal test cylinders were subjected to current pulses, up to 15 kA for the simulation of aircraft susceptibility to high transient currents and voltages. Surge current and corresponding dB/dt time functions were recorded during the tests (B is the magnetic flux density). The project is related to the electromagnetic (EM) compatibility performance of an aircraft in case of transient (i.e., surge) currents, such as lightning strokes. The paper reviews (step-by-step) the processing of surge current and dB/dt test data, and illustrates all steps with examples. Processing the test data makes the EM compatibility evaluation of the test results possible. Evaluation of the test results gives information on the magnitude and wave shape of transient EM field related quantities in the internal area of the fuselage of an aircraft that can result in EM interference with on-board electronics.

I. INTRODUCTION

The use of sensitive low voltage, solid state airborne equipment in an aircraft (and spacecraft as well) requires adequate protection of these devices from the transient voltages and currents induced in the fuselage created by the effects of lightning or directed energy applications. To do that it is necessary to know the nature and the magnitudes of the transient magnetic fields and currents during a transient event. For the understanding of the field build-up inside an aircraft the simulation of these surge currents is necessary. Basic structures, for instance metal test cylinders, can be used in order to simulate the simplified geometry of an aircraft fuselage [1-3]. Knowing the magnetic flux density (B) distribution inside the fuselage, when the surge current flows along it, is helpful to evaluate the EM compatibility performance of the airborne equipment in an aircraft. This is the starting point of studies of the effects of EM transients.

The main objectives of this paper are to describe the handling of test data generated by high surge current tests on a fuselage-like test setup, and to introduce the calibration steps of the measured data.

II. CALIBRATION OF THE TEST DATA

Custom designed probes placed onto the exterior or interior surface of the test cylinder representing an aircraft fuselage are used to measure dB/dt. The probe output voltage is proportional to the time derivative of the transverse flux passing through the area of the probe. The magnetic flux density time function is then determined as the integral of the induced voltage (also a time function) measured at the terminals of the probes. A two-axis dB/dt probe developed at The Ohio State University is shown in Figure 1.

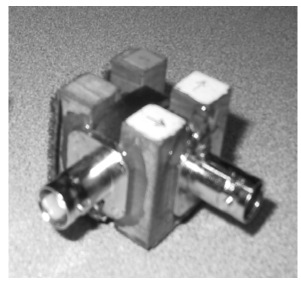

Figure 1. Picture of a dB/dt probe.

The output voltage of a dB/dt probe is usually reduced by attenuators in order to prevent clipping or damage to the fiber optic system and the oscilloscope. An amplifier may also be used with a dB/dt probe to increase a low magnitude signal. V_{rec} (receiver voltage) is the quantity measured by the oscilloscope. V_{rec} is directly proportional to the induced voltage in the coil, but attenuated or amplified by a certain factor. Since the output of a dB/dt probe is voltage vs. time, calibration of the data is necessary to obtain the B vs. time function.

III. CALIBRATION CALCULATIONS

A. dB/dt Probe Open Circuit Voltage Measurements

In order to obtain accurate dB/dt measurement results, calibration of the dB/dt probes is necessary. For that reason, in order to define the frequency response of each dB/dt probe, open circuit voltage measurements were performed at 5 kHz, 505 kHz and 1005 kHz by using a Hewlett-Packard 3577A network analyzer. Magnitudes per 1 mG, and phase angles were measured.

An example is given here in order to evaluate the open circuit voltage measurements. For one of the probe coils at 505 kHz, fV_0 = 1.367e-3 V/mG was measured. The probe constant for a typical coil is found by the following equation:

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14. ABSTRACT

In two laboratories, one high voltage and the other one high current, various metal test cylinders were subjected to current pulses, up to 15 kA for the simulation of aircraft susceptibility to high transient currents and voltages. Surge current and corresponding dB/dt time functions were recorded during the tests (B is the magnetic flux density). The project is related to the electromagnetic (EM) compatibility performance of an aircraft in case of transient (i.e., surge) currents, such as lightning strokes. The paper reviews (step-by-step) the processing of surge current and dB/dt test data, and illustrates all steps with examples. Processing the test data makes the EM compatibility evaluation of the test results possible. Evaluation of the test results gives information on the magnitude and wave shape of transient EM field related quantities in the internal area of the fuselage of an aircraft that can result in EM interference with on-board electronics.

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$$\frac{V_o}{f} = \frac{1.367x10^{-3}}{505,000} = 2.71x10^{-9} \text{ V/mG/Hz} \qquad (1)$$

In other words, for this probe at 1 Hz, $2.71x10^{-9}$ V is produced across the terminals of the probe for 1mG flux density inside the probe coil.

Figure 2 shows the R and X of the inner coil of a dual coil dB/dt probe with respect to frequency. At 500 kHz typically R ≅ 0.8 ohm and L ≅ 5 μH.

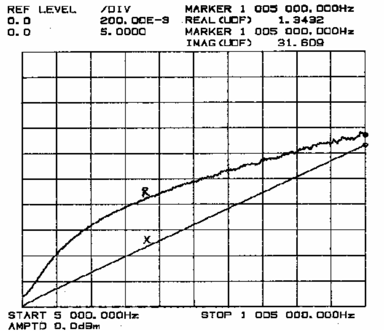

Figure 2. Resistance (upper trace, at 0.2 ohm/div.) and inductive reactance (lower trace, at 5 ohms/div.) change of the inner coil of a dB/dt probe with frequency.

B. Equivalent Circuit of the Measurement System

The equivalent circuit of the measurement system is represented in Figure 3.

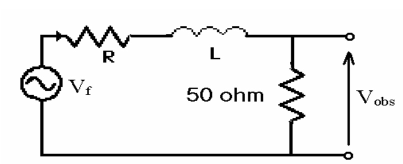

Figure 3. Equivalent circuit of the measurement system.

The following notations will be used in equations (1) to (12):

V_0 = open circuit probe output in V/mG/Hz
L = probe inductance in henries
R = probe resistance in ohms
G = voltage gain of optical amplifier and preamplifier
A = attenuator value = $10^{dB/20}$
f = frequency in hertz.

At a given magnetic flux density (B) and frequency (f) the open circuit probe output voltage can be represented as

$V_f = jBfV_0$ (2)

Here V_f = open circuit output voltage in volts at frequency f.

By using the equivalent circuit, which is shown in Figure 3, the input voltage to the attenuator, pre-amplifier or optical amplifier with an impedance of 50 ohms is

$$V_{50\Omega} = V_f \left[\frac{50}{j2\pi fL + R + 50} \right] \qquad (3)$$

The observed voltage (V_{obs}) at the oscilloscope is

$$V_{obs} = V_f \left[\frac{50}{j2\pi fL + R + 50} \right] \frac{G}{A} \quad \text{and} \qquad (4)$$

$jV_0 f =$ probe output at frequency f per mG.

$V_f = jBV_0 f =$ output for B in mG at frequency f.

By using these equations, B (magnetic flux density) can be calculated at a specific frequency:

$$jBV_o f = V_{obs} \left[\frac{j2\pi fL + R + 50}{50} \right] \frac{A}{G} \qquad (5)$$

$$B = \frac{V_{obs}}{jV_o f} \left[\frac{j2\pi fL + R + 50}{50} \right] \frac{A}{G} \qquad (6)$$

Since the recorded observed voltage data is available in the frequency domain, each component must be multiplied by the factor in (7) to obtain B for a specific measured coil voltage.

$$\frac{B}{V_{obs}} = \frac{1}{V_o f} \left[\frac{2\pi fL - j(R + 50)}{50} \right] \frac{A}{G} \qquad (7)$$

Figure 4 shows the changes in open circuit voltage magnitude and phase angle of a typical coil of a dual coil dB/dt probe.

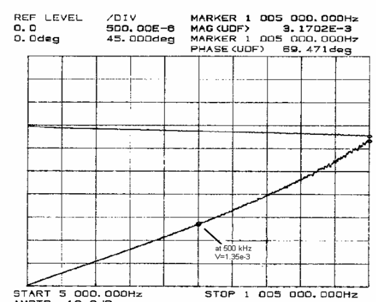

Figure 4. Open circuit voltage magnitude (lower trace, at 500 uV/div.) and phase angle (upper trace, at 45 deg./div.) change of the outer coil with frequency.

From Figure 5 the probe constant V_0 must be determined. Figure 5 shows that the voltage output of the probe can be assumed linear for frequencies between 0 and 500,000 Hz. For that reason, if f is between 0 and 500,000 Hz, then

$$\frac{V_f}{B} = V_{o1} f = \frac{V_1}{500,000} f \qquad (8)$$

For a typical probe coil V_1 = 1.35e-3 V/mG at 500 kHz (Figure 5).

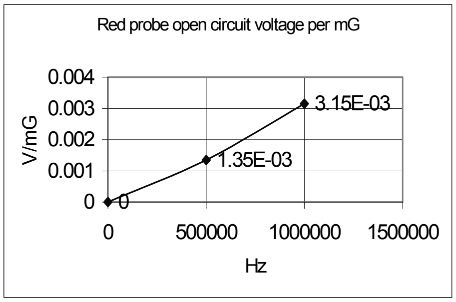

Figure 5. Open circuit probe voltage per mG, for frequencies between 0 and 1 MHz.

If f is between 500 kHz and 1 MHz, V_{02} can be calculated from Figure 5:

$$\frac{V_f}{B} = V_1 + \left[\frac{(V_2 - V_1)(f - 500,000)}{500,000} \right] \qquad (9)$$

Again, for a typical probe V_2= 3.15e-3 V/mG.

Thus, two values of V_f have been defined that are used for B (magnetic flux density) calculations as explained above.

The phase angle change with respect to frequency can be assumed to be a linear change. From Figure 4 for this specific probe coil the phase angle at 505 kHz is about 80 degrees. By using linearity a general formula can be found depending on the frequency. Since at 500 kHz the phase angle is 80 degrees the phase difference is 90-80=10 degrees. The phase angle vs. frequency expression is given by (10).

$$\varphi = 90^o (1 - \frac{10}{90} \frac{f}{500,000}) \qquad (10)$$

All calibration procedures for dB/dt probe coils have been explained above. In actual experiments the dB/dt probes are placed either inside or outside the test cylinder of the measurement set up. When these probes are exposed to magnetic field changes, a voltage is induced across their terminals. This voltage is transmitted to an oscilloscope by a fiber optic link consisting of a transmitter, receiver and cable. If necessary, some attenuators and amplifiers can also be used. Also, in order to obtain cleaner data, appropriate filters can be used depending on the noise level. The data displayed on the scope, is in the voltage vs. time format, and is saved in a disk file.

By using computer programs, the Fourier transform of the saved data can be performed. The frequency data must be multiplied by the following multiplier to obtain the magnetic flux density (B):

$$\frac{B}{V_{obs}} = \frac{1}{V_o f E} \left[\frac{j2\pi f L + R + 50}{50} \right] \frac{A}{G} \qquad (11)$$

where E is

$$E = e^{j\frac{\pi}{2}[1 - (10/90)(f/500,000]} \qquad (12)$$

IV. "SURGE" CODE

One of the programs that is used for data processing is called "SURGE." It was designed for processing dB/dt and current data produced by a simulated electric lightning surge.

In a typical case, there are about 2000 or 4000 points depending on the oscilloscope sampling time and recording time.

The recorded dB/dt curves usually include some time period before the beginning of the output voltage. To evaluate the results correctly, the time delay before the voltage starting point, as well as the dc offset must be eliminated. In addition, the data has to be calibrated by using data processing methods already described. Besides this, sometimes it might be necessary to filter out the high frequency noise to get clearer and more accurate results.

V. PROCESSING THE dB/dt DATA BY USING THE "SURGE" PROGRAM

The "SURGE" program is able to process the dB/dt time functions and current data.

In a typical case, there are about 2000 or 4000 points for the recorded data during the measurements. Figure 5 shows a typical dB/dt probe output.

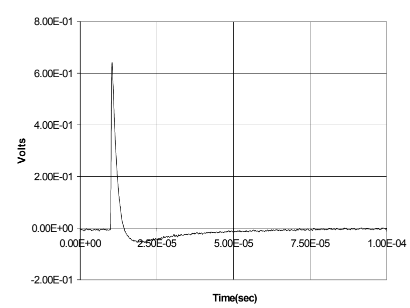

Figure 6. Typical dB/dt probe output.

When the dB/dt probe outputs are processed, there are several features to consider. For cases where the current returns to zero within the recorded time window, the average value of dB/dt must be zero.

If the recording fiber optic system has an arbitrary dc offset, then the first processing step should be to remove that. Assuming a positive polarity surge current, the dB/dt data should start at zero, showing a sharp positive spike while the current is rising, and a small negative value while it is falling, eventually dropping to zero.

First, the start-of-rise point of the dB/dt vs. time function should be moved to the (0,0) point of the chart. For that purpose, an appropriate program command is used for the points before the start-of-rise point, in order to find the zero amplitude level. (Averaging is necessary to eliminate the noise.) After finding the average value, another command can be used to shift that average level to zero. For Figure 6 since the corresponding current goes to zero, the average of dB/dt has to be zero.

Second, where the current has a peak (maximum) value the dB/dt has to have its zero crossing because the integral of dB/dt should give the same trend of the current wave shape.

Third, the original record contains some time before the start-of-rise of the voltage output. This beginning part should also be removed from the curve.

The last step of processing the dB/dt data is to calibrate it and filter some noise out. For filtering purposes the Fourier transform of the modified dB/dt curve must be performed. After performing the Fourier transform the probe output is in the frequency domain. Low-pass filtering can be used then; it ramps linearly from 200 kHz to 400 kHz. At 200 kHz the amplitude is not changed, but at 400 kHz the amplitude is zero. After that, the magnetic flux density probe output is a less noisy function.

For calibration purposes (calibration means integration as well) each dB/dt point in the frequency domain must be multiplied by a complex number obtained as explained before in Equations (11, 12).

Before calibration, the Fourier transformation of the data is performed by using the appropriate command in the “SURGE” program. To do that the size of the data must be 2^n (n=1, 2, 3…). As mentioned before, the measurement data usually contains 2000 or 4000 points. To perform the Fourier transformation the number of the data points must be changed. To interpolate the data, another command can be used for increasing or decreasing the number of points. After obtaining 2^n data points, the Fourier transformation process can be applied..

After calibration and filtering the data is returned to the time domain using the inverse Fourier transformation. A new command will perform this process in the "SURGE" program, with the results available in the time domain.

After the calibration procedure has been applied, the magnetic flux density vs. time curve is obtained. The calibrated and filtered output of Figure 6 is given in Figure 7.

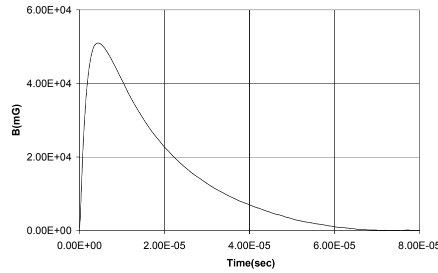

Figure 7. Filtered and calibrated dB/dt probe output; B vs. time function.

VI. CONCLUSIONS

A technique for processing test data obtained during transient current and dB/dt measurements has been described.

The measurement results were successfully processed by using the appropriate procedure and computer codes.

Processing the test data makes the EM compatibility evaluation of the test results possible. Evaluation of the test results gives information on the magnitude and wave shape of transient electromagnetic field related quantities in the internal areas of the fuselage of an aircraft.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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